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Biomechanical and Physiological Validation of the Omni-Directional Treadmill Upgrade as a Mobility Platform for Immersive Environments

by Angela C. Boynton, Kathy L. Kehring, and Timothy L. White

ARL-TR-5510 **April 2011**

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14. ABSTRACT
A novel mobility platform, the Omni-Directional Treadmill (ODT) Upgrade, has been developed to allow users to move through a virtual environment in a manner equivalent to doing so in the real world. The purpose of this investigation was to determine the extent to which walking on the ODT Upgrade is comparable to walking overground for selected biomechanical and physiological variables. Temporal-spatial parameters, sagittal plane joint kinematics, and metabolic cost were assessed for 10 subjects as they walked along identical circular courses overground and on the ODT Upgrade. Except for a reduction in ankle plantarflexion following toe-off on the ODT Upgrade, differences in gait mechanics between the overground and ODT Upgrade trials were relatively small. However, oxygen consumption was more than 20% greater during walking on the ODT Upgrade than overground, and must be taken into account when comparing the results of training and research conducted on the ODT Upgrade to that of the real world. Future studies are required to develop a better understanding of the potential mechanisms behind this substantial increase in metabolic cost. In conclusion, the ODT Upgrade permits users to walk through a virtual environment in a relatively natural way but with a significant increase in physiological demand.

15. SUBJECT TERMS
omni-directional treadmill, gait, metabolic cost, immersive simulation, mobility interface

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Contents

List of Figures

List of Tables

1. Introduction

Technological advances in computer graphics combined with the development of large rear-projection surround displays have enabled the creation of virtual environments that visually immerse the user into a sense of real-world presence. Integration of these visual displays with a mobility interface that enables the user to move through the virtual environment provides instrumentation for more interactive applications. The mobility interface can be as simple and abstract as a mouse or a joystick. However, given their inability to provide appropriate effects on the user from the physical workload of traversing terrain and their distraction from the psychosomatic immersion into the environment, these interfaces may not be adequate for applications that require or benefit from natural human locomotion through the three-dimensional (3-D) environments. A simulation environment that provides a realistic perception of movement and the effects of fatigue would enhance the U.S. Army's ability to gain insight into the physical, physiological, and cognitive processes of dismounted Soldiers when placed in demanding, stressful operational situations. It would provide a means to explore new operational tactics or equipment concepts in a highly configurable, repeatable, and safe manner and to collect data that would be difficult or impossible to gather from real-world exercises.

1.1 Background

Over the years, more complex mobility platforms have been developed, attempting to achieve greater equivalence between the user's motions on the device and those used in the real environment. These designs have ranged from unicycle-type devices, to standing bipedal devices, to treadmill-based devices (Crowell et al., 2006). The Omni-Directional Treadmill (ODT), which allows the user to turn and travel in any direction without leaving a confined workspace, is one device that shows promise for providing natural locomotion to the user. However, to be truly effective at simulating the real-world experience of traversing the environment, the biomechanical and physiological effects on the user should be the same as those in the real world.

1.2 Conventional Treadmills

Over the past three decades, multiple biomechanical and physiological evaluations have been conducted between walking overground and on a conventional treadmill (Alton et al., 1998; Lee and Hidler, 2008; Murray et al., 1985; Parvataneni et al., 2009; Pearce et al., 1983; Riley et al., 2007; Warabi et al., 2005); however, there does not currently appear to be consensus as to what, if any, differences exist between the two. With respect to temporal-spatial variables, increased cadence and decreased stance time during treadmill walking appear to be the only consistent findings. Although statistically significant decreases in swing time (Lee and Hidler, 2008) and stride length (Pearce et al.) have also been reported, other researchers have found these

differences to be either nonexistent or to show a trend in the opposite direction (Alton et al.; Murray et al.; Parvataneni et al.; Riley et al.).

Of those studies evaluating overall sagittal plane joint excursions (Alton et al., 1998; Lee and Hidler, 2008; Parvataneni et al., 2009), no significant differences were observed, with the exception of one finding of increased hip ROM (Alton et al.) and one of decreased knee excursion (Lee and Hidler). A 3° to 4° increase in peak hip flexion was reported by both Alton et al. and Parvataneni et al., while Riley et al. (2007) found peak hip flexion to be reduced by <1°, and Lee and Hidler found no difference. Murray et al. (1985) and Riley et al. both reported a significant reduction in hip extension during treadmill walking; however, other researchers found no difference between the two conditions. Findings for peak knee angles appear to be more consistent across studies, with no difference found for peak flexion and two reports of small but significant decreases in peak extension values (Parvataneni et al.; Riley et al.) during treadmill walking. With the exception of one report of a 3° increase in dorsiflexion (Murray et al.), peak ankle angles have generally been reported to be similar between overground and treadmill walking (Alton et al.; Lee and Hidler; Parvataneni et al.; Riley et al.). Riley et al. and Lee and Hidler additionally evaluated differences in kinetics during overground and treadmill walking. A lack of difference in peak ankle power and significant decrease in peak knee extensor moment and braking ground reaction force were the only similar findings between the two studies.

The effect of treadmill walking on muscle activity was investigated by Murray et al. (1985) and Lee and Hidler using two different mathematical methods. Murray et al. calculated the average electromyographic (EMG) signal over the entire gait cycle for several muscle groups and found activity in the quadriceps alone to be increased during the treadmill condition. In Lee and Hidler's study, the gait cycle was broken into seven segments, and the integral of the EMG signal (iEMG) was calculated independently for each of those time periods. Similar to the findings of Murray et al., quadriceps activity during the last half of the gait cycle was higher on the treadmill. However, the iEMG of several other lower extremity muscles was also found to be significantly different on the treadmill at various points within the gait cycle.

Finally, with respect to physiological differences, treadmill walking has been found to have no effect on heart rate (Murray et al., 1985) to increase it (Parvataneni et al., 2009) and decrease it (Pearce et al., 1983). Murray et al. and Pearce et al. additionally found no difference in oxygen consumption between the two conditions; however, Parvataneni and colleagues reported a 23% increase in metabolic cost during treadmill walking.

1.3 Omni-Directional Treadmills

The U.S. Army Research Laboratory-Human Research and Engineering Directorate (ARL-HRED) evaluated the energy expenditure on the first-generation design of the ODT (Virtual Space Devices Inc., Bloomington, MI, figure 1). The design of the first-generation ODT employs two belts arranged perpendicularly, one inside the other (figure 1). The top belt consists

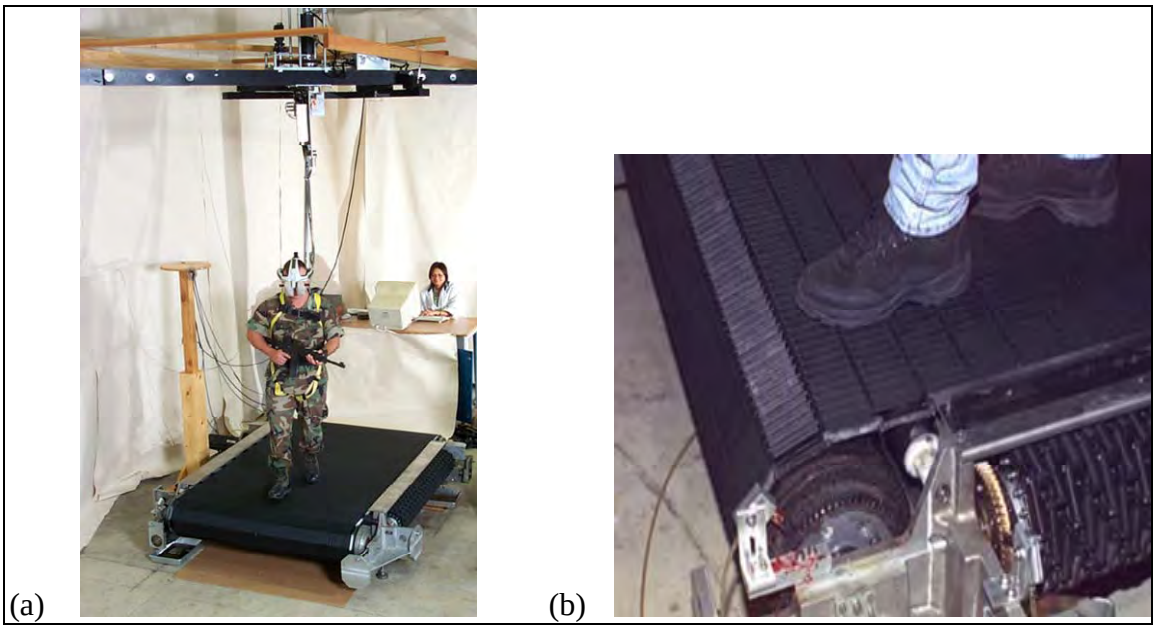

Figure 1. First-generation ODT (a) and first-generation ODT belt configuration (b).

of rollers that freely rotate perpendicular to the direction of travel of the belt. The rollers on the top belt rotate through contact with the lower moving belt. Therefore, the recentering movement of the user in one axis is caused by the rotation of the rollers, while movement in the other axis is caused by the travel of the top belt; both can occur simultaneously. This allows the user of the ODT to move in any direction while remaining within the 4- × 4-ft working surface. Another major difference between the ODT and conventional treadmills is that the speed at which the ODT's belts move are in response to the movement of the user rather than being set to a constant value. For the energy expenditure evaluation, the participants traversed two different courses: a simulated course on the ODT where the environment was viewed on a head-mounted display (HMD) and a similar real-world indoor course. They traversed the courses at two different speeds and while carrying two different loads. Oxygen uptake, heart rate, and rating of perceived exertion (RPE) were measured and compared (Crowell et al., 2006). As expected, all three measures increased with increasing speed and load. All three measures were also higher on the first-generation ODT than on the real-world course. Oxygen uptake increased 17.8%, heart rate increased 8.6%, and RPE increased 25.6%. The researchers felt that the greater physiological demand to walk on the ODT may be caused by the users feeling unstable or unbalanced, causing them to activate more muscles to maintain stability. This may be due to problems with the control system misinterpreting the user's upper body motions and initiating "false starts," or overshooting the center resulting in repeated overcorrecting movements of the belts. Additionally, the control system did not allow the user to make sharp turns and fine movements easily. They also thought the reduced field of view (FOV) associated with the HMDs may have contributed to the users straying off the course and having to move faster to

maintain the pace. Darken et al. (1997) performed a limited human factors evaluation of the ODT. Their findings were based on observations from videotapes of a single user performing a set of locomotion tasks on the ODT. They concluded that "users of the ODT must learn how to walk on the ODT," and that it was readily apparent that the locomotion was not the same as the real world.

Recommendations were made for improvements to the first-generation ODT, resulting in the Omni-Directional Treadmill Upgrade (MTS Systems Corp., Eden Prairie, MN, and Virtual Space Devices Inc., figure 2), which ARL-HRED received in September 2006. As opposed to the roller design used in the first-generation ODT, the ODT Upgrade incorporates a series of 80 4-in-wide mini-belt segments attached perpendicularly to the underlying main belt (figure 2). The main belt travels in the x-axis. The mini-belts travel with the main belt but also operate like mini-treadmills to generate movement in the y-axis. The operation of the mini-belts (y-axis) and the main belt (x-axis) is controlled by two separate motors so they can move independently and simultaneously to recenter the user. Improvements were made to the control system of the ODT Upgrade by incorporating a washout algorithm and fuzzy logic systems (Hessburg and Clark, 2005). The washout algorithm attempts to allow the users to feel the expected motion cues of their various gaits, while minimizing their perception of the movement needed to maintain their position in the workspace. The fuzzy logic is used to determine the gait of the user (i.e., walking forward, walking backward, etc.) and adjust the parameters of the washout algorithm accordingly. The size of the working surface was increased to 8 × 8 ft, which could enable a slower, less perceptible speed to return the user to the center. ARL-HRED has integrated the ODT Upgrade into a CAVE Automatic Virtual Environment with large rear projection screens for visually displaying the virtual environment. This provides a more natural FOV as opposed to the HMDs and permits users to see their feet. The noise levels produced by the ODT Upgrade are also lower than those produced by the first-generation ODT, which may be less distracting to users and allow them to better hear the sounds from the virtual environment.

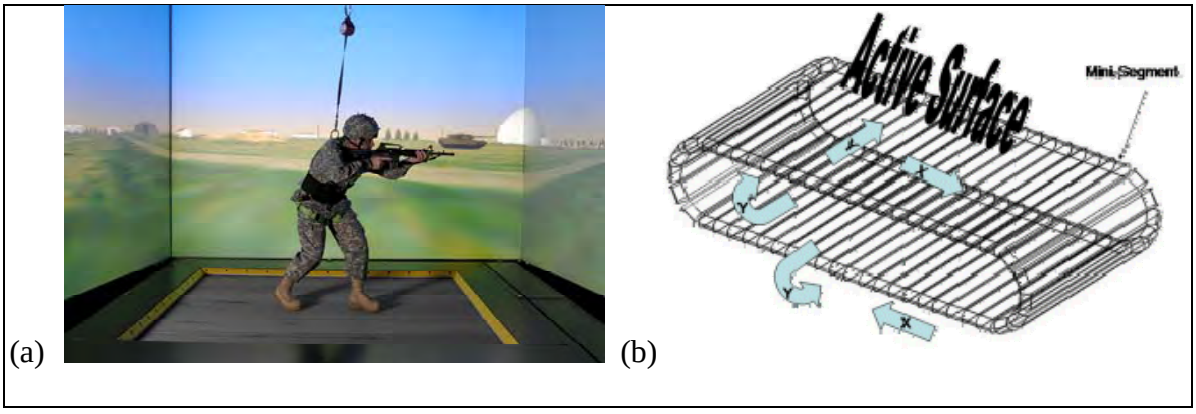

Figure 2. ODT Upgrade (a) and ODT Upgrade belt configuration (b).

1.4 Objective

The ability of the ODT Upgrade to impose biomechanical and physiological effects on the user that are similar to those experienced in the real world is unknown. The purpose of this investigation was to determine whether walking on the ODT Upgrade is comparable to walking overground for selected biomechanical and physiological variables, quantify any significant differences, and determine if those differences are affected by walking speed. This was accomplished by using a within subjects 2 × 2 experimental design with two levels of terrain (ODT and overground) and two walking speeds (1.12 and 1.34 $m \cdot s^{-1}$).

2. Materials and Methods

2.1 Participants

Six male and four female civilian employees of ARL-HRED volunteered to participate in this investigation (table 1). The participants read and signed a statement of informed consent* and self-reported that they were physically fit to complete the study protocol. Participants also completed a motion sickness questionnaire (appendix A) to obtain a baseline for comparison with symptom levels experienced during the study and at the conclusion of testing (Kennedy et al., 1992).

Table 1. Participant characteristics.

Participant	Age (years)	Mass (kg)	Height (cm)	Leg Length (cm)
Males (n = 6)	42.2 (9.7)	86.3 (15.0)	179.2 (6.2)	96.4 (5.4)
Females (n = 4)	38.0 (3.8)	61.3 (6.9)	163.8 (8.5)	89.4 (4.9)
All (n = 10)	40.5 (7.8)	76.3 (17.6)	173.0 (10.4)	93.6 (6.1)

Note: Values are group mean (standard deviation).

2.2 Instrumentation

2.2.1 Immersive Environment Simulator

Located at Aberdeen Proving Ground, MD, the Immersive Environment Simulator (IES) (figure 3) consists of a second-generation ODT (ODT Upgrade, MTS Systems Corp., and Virtual Space Devices Inc.) integrated with a reconfigurable display system (RAVE II, Fakespace Systems, Kitchner, Ontario, Canada) and camera-based motion tracking system (Vicon Motion Systems, Inc., Lake Forest, CA). The 8- × 8-ft working surface of the ODT upgrade, made up of 80 mini-belts that move perpendicularly to a main belt, allows the user to walk, jog, or even

* The investigators have adhered to the policies for the protection of human subjects as prescribed in AR 70-25 (1990).

Figure 3. Immersive environment simulator.

crawl in any direction. Folding the four 12.5- × 10-ft rear-projected screens in at 90° to one another completely immerses users in the virtual environment and provides them with a full 360° FOV. Clusters of reflective markers attached to a helmet and a rigid plate on the back of a neoprene waistband are tracked in real-time by the Vicon system. The position and attitude of the helmet are used to determine the user's eyepoint and adjust the perspective of the display accordingly, while the speed and heading of the rigid plate are used to determine how the belts of the ODT Upgrade should move to return the user to the center of the workspace.

2.2.2 Three-Dimensional Motion Capture

Temporal-spatial and kinematic variables during walking on the ODT Upgrade and overground were assessed using the 3-D trajectories of retroreflective markers attached to each participant's pelvis, legs, and feet (figure 4). Individual tracking markers were placed bilaterally on the anterior superior iliac spines, anterior and lateral aspects of the thighs and shanks, lateral femoral condyles and malleoli, heels, and first metatarsophalangeal joints. A marker located at the middle of the bottom edge of the back belt used by the ODT Upgrade control system was aligned with the sacrum. For the purpose of defining the segments and their coordinate systems, anatomical markers were also placed over the medial femoral condyles and malleoli during a static standing trial and then removed for the walking trials. During the ODT Upgrade trials, marker trajectories were recorded and tracked using a Vicon Peak 460 motion capture system (Vicon Motion Systems, Inc.) consisting of six M2 cameras and Workstation 5.2.4 software. For the overground trials, six Falcon cameras and EVaRT 4.0 software (Motion Analysis Corporation, Santa Rosa, CA) were used. In order to reduce any potential issues associated with using two different systems, all data for a given participant were collected within a single session (i.e., identical marker set for all trials), and both systems were fully calibrated prior to each data collection session. Motion capture data were collected at a sampling rate of 60 Hz approximately every 45 s for 10 s throughout each trial.

Figure 4. Placement of tracking and anatomical markers.

2.2.3 Physiological Demand Assessment

Oxygen consumption was measured using a K4b^2 portable cardiopulmonary exercise testing system (Cosmed USA, Chicago, IL) and its associated software. The K4b^2 system collects and samples exhaled gases breath-by-breath using a facemask and small-diameter tubing connected to the main unit, which is positioned on the participant's chest along with the battery pack (figure 5). O_2 and CO_2 concentrations of the expired gases were stored to the main unit throughout each walking trial and then downloaded to the Cosmed software for further analysis.

Figure 5. The participant wears a facemask and Cosmed K4b^2.

2.3 Data Collection Protocol

Data were collected while participants walked at ~1.12 m•s^{-1} (2.5 mph) and 1.34 m•s^{-1} (3.0 mph) on the ODT Upgrade and overground for 5-min periods. The order in which the conditions were presented to the participants was counterbalanced to minimize learning and fatigue effects. For the overground trials, the participants walked along a circular path with a radius of 14 ft (figure 6a) while following an investigator pushing a pacing wheel at the appropriate speed. For the ODT Upgrade trials, a model of the room in which the overground trials occurred containing a dimensionally identical circular course was displayed on the RAVE II screens. The monoscopic display was at a resolution of 1280 ×1024 and a frame rate of 60 Hz. An avatar moved along the course in front of the participants to help them maintain the appropriate speed (figure 6b).

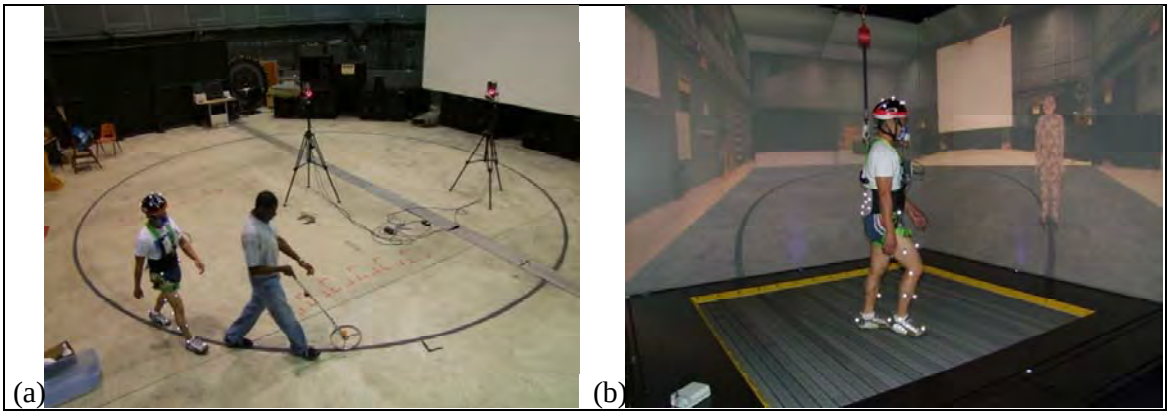

Figure 6. The participant follows an investigator during the overground trials (a) and a virtual 3 entity during ODT Upgrade trials (b).

Prior to beginning the data collection session, the participants were given an opportunity to practice walking on the ODT Upgrade. They were first fitted with a safety harness, helmet, and neoprene belt. Next, an investigator familiarized participants with the operation of the device and all of the safety and emergency stopping procedures available to them and the operator. The participants were then allowed to walk in all directions on the ODT Upgrade until they felt comfortable doing so and appeared to have no hesitation or issues with their balance. Once comfortable operating the ODT Upgrade, the participants practiced following the avatar along the circular course in the virtual environment until they were capable of consistently maintaining the correct pace. The participants typically required less than a half hour to become proficient at negotiating the course.

Following the participants' training session, reflective tracking markers were applied to their hips, legs, and feet, as previously described. The participants were then fitted with a facemask and heart rate monitor chest strap and donned the K4b^2 unit. Once all equipment was in place, the participants were given an opportunity to acclimate themselves with breathing into the facemask. Next, static calibration trials were collected in both the ODT Upgrade and overground motion capture volumes, followed by removal of the medial knee and ankle markers. Finally, the participants began the first of their 5-min data collection trials. Participants were given a minimum 10-min break between trials to allow their heart rate and energy expenditure to return to baseline values. During each break, the participants also provided an RPE for the trial they had just completed using the Borg scale (appendix B).

After completion of the data collection trials, participants were asked again to fill out the motion sickness questionnaire shown in appendix A. If any of the motion sickness symptoms were elevated from those reported prior to the start of the trials, participants were asked to rest quietly. The questionnaire was then repeated every 15 min until the symptoms subsided, at which time, participants were released from the study.

2.4 Data Reduction and Analysis

Reflective marker trajectories were reconstructed and labeled in either Workstation (ODT Upgrade) or EvaRT (overground) and then exported to c3d files. Oxygen consumption (mL $O_2 \bullet min^{-1}$) data were exported from the Cosmed software into tab-delimited text files. As described next, the remainder of the signal processing and data reduction was performed using a series of custom programs written in LabVIEW 8.2 (National Instruments, Austin, TX).

The tracked reflective marker data were first smoothed at a cutoff frequency of 6 Hz using a fourth-order, zero-lag, low-pass Butterworth filter. Due to the lack of ground reaction force data, heel strike (HS) and toe-off (TO) events were determined using a velocity-based algorithm (Zeni et al., 2008) applied to the heel marker trajectories in the pelvic coordinate system. HS was defined as the time at which the anterior-posterior component of the heel marker velocity transitioned from positive to negative, and TO was defined as the time at which the anterior-posterior component of the toe marker velocity transitioned from negative to positive.

Several temporal-spatial parameters were then calculated bilaterally for each gait cycle: stance time (TO-HS), swing time (HS-TO), toe-off (stance time/[stance time + swing time] × 100), cadence (120/[stance time + swing time]), and walking speed ([stride length × cadence]/120). Due to the manner in which the ODT Upgrade operates and the fact that the participants were walking on a slight curve in both environments, stride length was calculated as the sum of the anterior-posterior excursion of the heel marker with respect to the pelvic coordinate system from HS to TO and from TO to HS. To account for differences in stature and leg length between participants, stride length and cadence were additionally normalized using the following equations (Hof, 2006):

$$stride\ length_{norm} = stride\ length/l\ , \tag{1}$$

and

$$\text{cadence}_{\text{norm}} = \text{cadence}\ \times \sqrt{l/g}\ , \tag{2}$$

where l is the participant's leg length in meters (calculated from the vertical position of the participant's hip joint center in the static trial) and g is 9.81 $m \cdot s^{-2}$.

Sagittal plane Euler joint angles were also calculated for the hips, knees, and ankles and time normalized to 100 points over each gait cycle. The similarity of each participant's mean joint angle curves from the ODT Upgrade trials as compared to the overground trials was determined from four measures: trend normalcy, range amplitude ratio, range offset, and phase offset. The methodology behind the calculation of these measures is described in detail by Crenshaw and Richards (2006) and summarized here. *Trend normalcy* represents similarity in the shape of two curves independent of any differences in their magnitude. It is determined from the ratio of variability about and along an eigenvector calculated from the singular value decomposition of a square matrix formed by multiplying the transpose of a matrix containing both waveforms by itself (M^TM). As presented here, a trend normalcy value of 1 indicates that the two curves are identical in shape. *Range amplitude ratio* compares the overall range of motion (ROM, max value – min value) of the two curves and is simply calculated by dividing the ROM of the curve of interest (i.e., ODT Upgrade) by that of the normative curve (i.e., overground). Therefore, a range amplitude ratio of 1 indicates no difference in ROM, while a value >1 indicates a larger ROM, and a value <1 indicates a smaller ROM for the curve of interest, compared to the normative curve. Subtracting the mean value of the normative curve from that of the curve of interest gives us the *range offset*. A positive value indicates a more flexed operating range for the curve of interest, while a negative value indicates more extension compared to the normative curve. Finally, *phase offset* is the percentage of the gait cycle that the curve of interest must be shifted by in order to maximize trend normalcy. A positive value indicates that the curve of interest must be shifted to the right, while a negative value indicates that shift to the left is required.

Raw oxygen consumption data were first normalized to the participant's body mass. Mean normalized oxygen consumption was then calculated over the last minute of data from each trial.

2.5 Statistical Analyses

The design of this study is within subjects with two independent variables, each having two levels: terrain (ODT Upgrade and overground) and walking speed (1.12 and 1.34 $m \cdot s^{-1}$). Descriptive statistics were calculated for participant characteristics, RPE responses, and all other variables of interest. Due to the course being circular rather than straight, values for the left and right legs were analyzed separately. An overall significance level of 0.05 was used for all comparisons.

A multivariate analysis of variance with *post hoc* analyses of significant results was used to assess the main effect of terrain on the temporal-spatial measures at each walking speed. With respect to sagittal plane joint angles, 95% confidence intervals were first determined for trend normalcy, phase offset, range amplitude ratio, and range offset of joint angles during overground walking by analyzing the individual curves for each participant with respect to the group mean at each walking speed. Each participant's mean joint angle curves from the ODT Upgrade conditions were then analyzed for normalcy in comparison to the group mean curves from the overground conditions. Those falling outside of the 95% confidence intervals were identified. Finally, the effect of terrain on normalized oxygen consumption and on RPE at each walking speed was individually assessed using paired t-tests.

3. Results

3.1 Temporal-spatial

Left and right temporal-spatial parameter values during walking overground and on the ODT are shown in table 2. As previously described, cadence and stride length are normalized and therefore nondimensional. While slightly higher than the target values for each walking speed condition, the calculated speeds were not significantly different between terrain conditions. Terrain condition was found to have a significant main effect ($p = 0.038$), only at the faster walking speed. Left and right swing time ($p = 0.011$ and 0.024) and left stride length ($p = 0.029$) were significantly shorter during walking on the ODT than overground at 1.34 $m \cdot s^{-1}$. As a consequence of the decreased left stride length, cadence for the left leg was significantly greater on the ODT ($p = 0.006$).

Table 2. Temporal-spatial parameters.

Parameter		1.12 m/s (2.5 mph)		1.34 m/s (3.0 mph) [a]	
		Overground	ODT	Overground	ODT
Speed (m/s)	Left	1.27 (0.08)	1.27 (0.08)	1.45 (0.10)	1.44 (0.15)
	Right	1.22 (0.08)	1.23 (0.11)	1.40 (0.10)	1.42 (0.17)
Cadence	Left	35.7 (0.6)	37.7 (3.2)	37.2 (1.3)	39.8 (2.4) [b]
	Right	33.5 (1.9)	34.6 (2.7)	35.3 (2.1)	37.4 (2.8)
Stance time (s)	Left	0.74 (0.03)	0.72 (0.05)	0.69 (0.03)	0.65 (0.05)
	Right	0.75 (0.03)	0.72 (0.04)	0.69 (0.03)	0.65 (0.05)
Swing time (s)	Left	0.39 (0.02)	0.37 (0.03)	0.38 (0.02)	0.35 (0.02) [b]
	Right	0.39 (0.01)	0.37 (0.03)	0.38 (0.02)	0.35 (0.03) [b]
Stride length	Left	1.45 (0.09)	1.38 (0.12)	1.54 (0.07)	1.43 (0.12) [b]
	Right	1.39 (0.08)	1.35 (0.16)	1.48 (0.07)	1.42 (0.14)
Toe-off (% cycle)	Left	65.4 (0.9)	65.8 (0.4)	64.6 (0.8)	65.2 (0.8)
	Right	65.6 (0.6)	66.0 (0.8)	64.5 (0.6)	64.8 (0.9)

Note: Values are group mean (standard deviation).
[a] Main effect of terrain.
[b] Significantly different from overground condition.

3.2 Kinematics

Mean sagittal plane hip, knee, and ankle joint angles during walking overground and on the ODT at 1.12 and 1.34 m/s are presented in figures 7 and 8, respectively. The trend normalcy, range amplitude, range offset, and phase offset values resulting from the comparison of the ODT joint angle curves to those obtained during overground walking can be found in table 3, along with the 95% confidence intervals for each parameter.

The general shape of the joint angle curves for the ODT condition is quite similar to those for the overground condition during walking at both speeds. Only the right ankle produced a trend normalcy value that was substantially outside of the 95% confidence interval for overground walking. The overall sagittal plane range of motion at the hip and knee are also comparable between the two terrain conditions (i.e., range amplitude near 1). At the ankle, however, the range amplitude ratio is between 0.78 and 0.85, indicating a roughly 20% reduction in ankle ROM during walking on the ODT. The majority of this difference appears to be due to a decrease in the amount of plantarflexion achieved immediately following toe-off (figures 7 and 8). The greatest difference between the kinematics for the two terrain conditions is in the overall amount of flexion at all three joints. Both hips, both knees, and the right ankle are up to 5% more flexed throughout the entire cycle of walking on the ODT than overground.

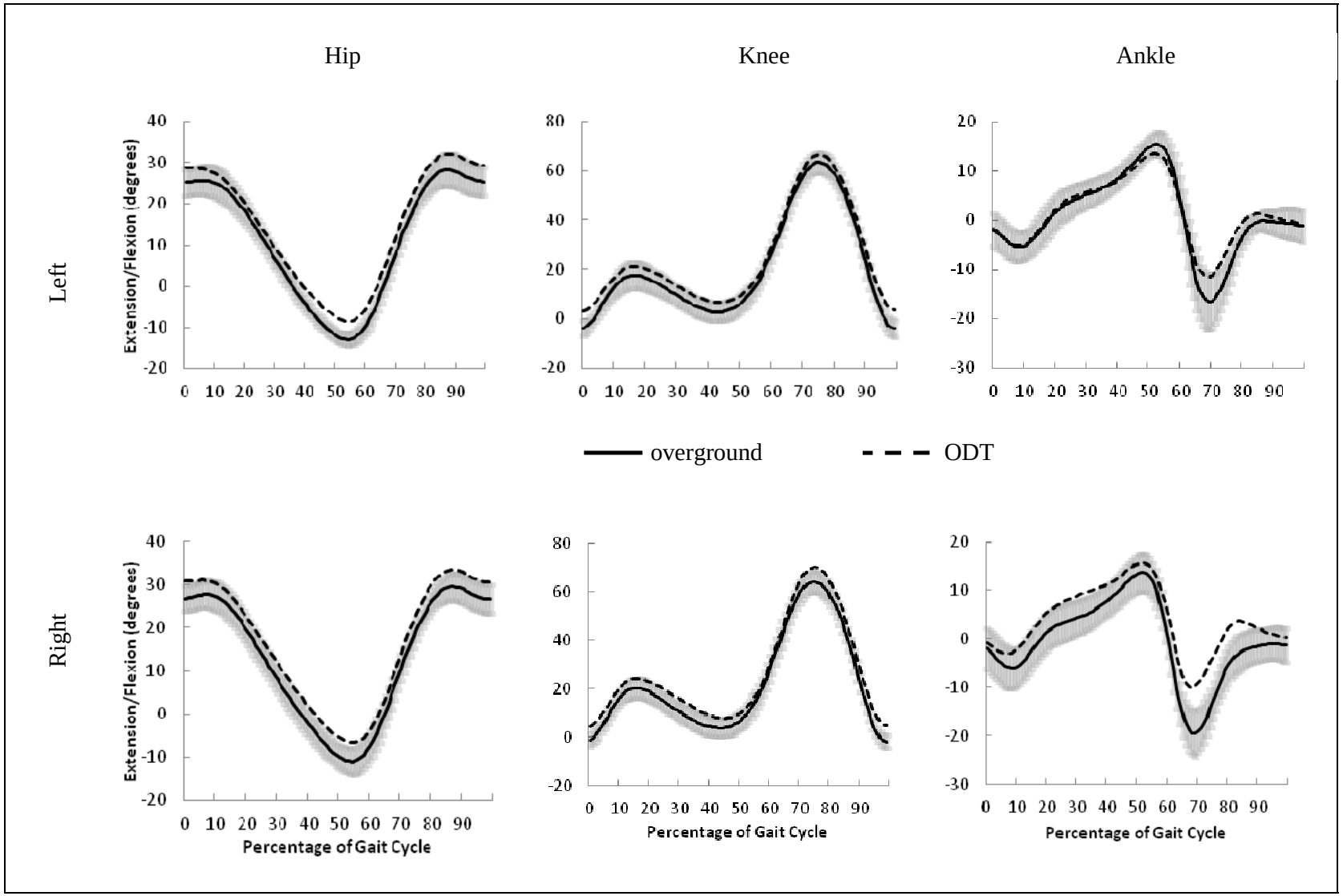

Figure 7. Mean sagittal plane hip, knee, and joint angles during walking at 1.12 m/s overground and on the ODT. Shaded area represents 1 standard deviation above and below the overground mean.

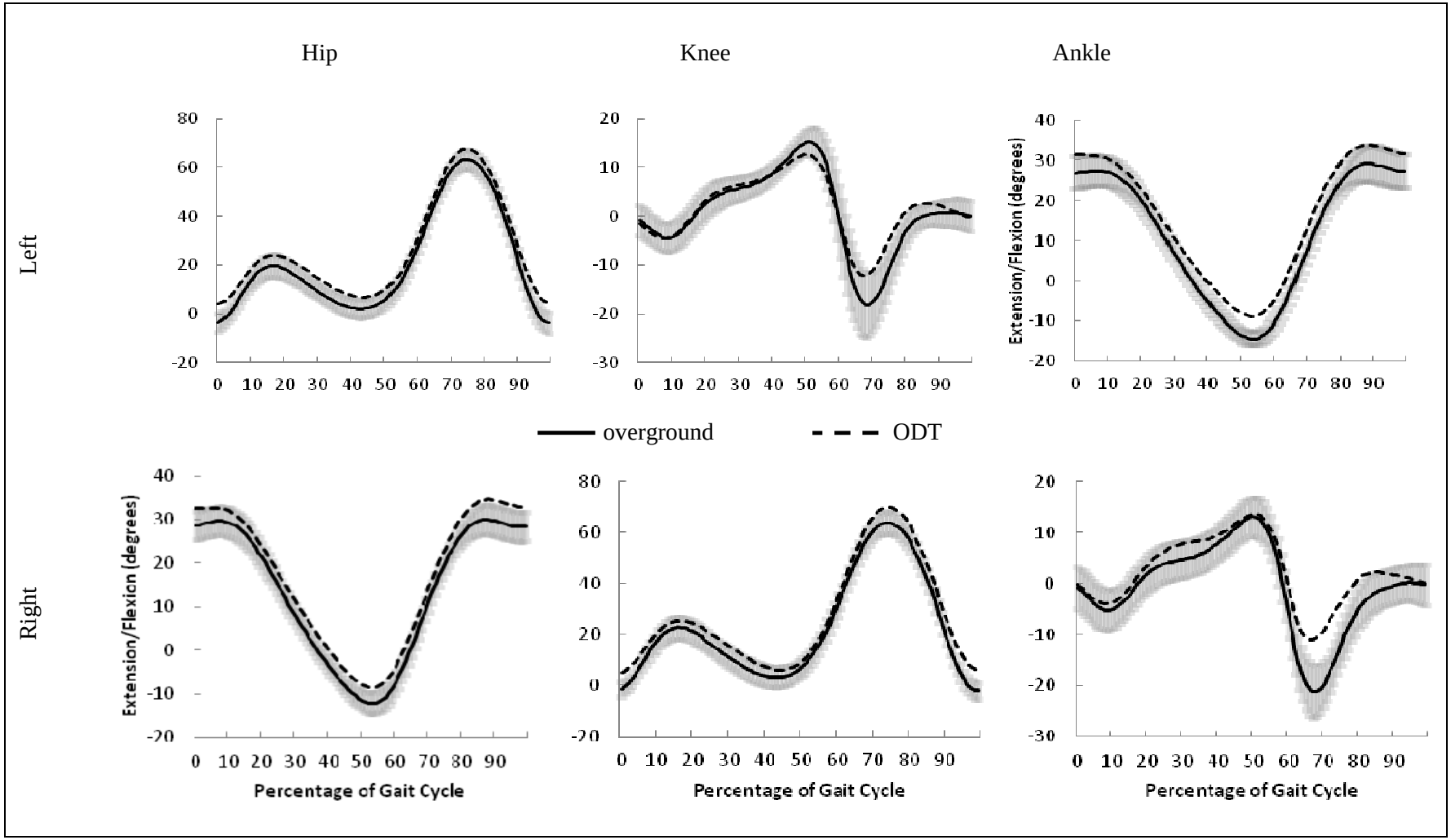

Figure 8. Mean sagittal plane hip, knee, and joint angles during walking at 1.34 m/s overground and on the ODT. Shaded area represents 1 standard deviation above and below the overground mean.

Table 3. Sagittal plane joint angle normalcy during walking on the ODT.

Parameter			1.12 m/s (2.5 mph)		1.34 m/s (3.0 mph)	
			Mean (standard deviation)	**95% CI[a]**	**Mean (standard deviation)**	**95% CI[a]**
Hip	Trend normalcy	Left	0.998 (0.001)	0.996, 1	0.998 (0.001)	0.996, 1
		Right	0.997 (0.002)	0.995, 1	0.997 (0.002)	0.997, 1
	Range amplitude (ODT/OG)	Left	0.99 (0.03)	0.95, 1.06	0.97 (0.05)	0.97, 1.06
		Right	0.99 (0.08)	0.97, 1.06	1.01 (0.06)	0.97, 1.07
	Range offset (degrees)	Left	**3.46 (2.11)**	–1.66, 1.66	**4.50 (3.00)**	–1.71, 1.71
		Right	**3.75 (3.08)**	–1.95, 1.95	**3.52 (1.86)**	–1.80, 1.80
	Phase offset (% gait cycle)	Left	0.20 (0.8)	–0.61, 0.81	0.40 (0.52)	–0.58, 0.58
		Right	–0.10 (0.57)	–0.61, 0.81	0.20 (0.79)	–0.30, 0.50
Knee	Trend normalcy	Left	0.992 (0.007)	0.992, 1	0.994 (0.004)	0.992, 1
		Right	**0.992 (0.006)**	0.993, 1	**0.989 (0.010)**	0.993, 1
	Range amplitude (ODT/OG)	Left	**0.96 (0.03)**	0.97, 1.04	**0.96 (0.05)**	0.97, 1.00
		Right	1.00 (0.07)	0.97, 1.04	1.01 (0.06)	0.98, 1.03
	Range offset (degrees)	Left	**3.84 (2.45)**	–2.55, 2.55	**4.86 (3.14)**	–2.60, 2.60
		Right	**4.53 (3.89)**	–2.44, 2.44	**4.47 (3.56)**	–2.60, 2.60
	Phase offset (% gait cycle)	Left	**–0.40 (0.52)**	–0.31, 0.51	–0.20 (0.42)	–0.31, 0.51
		Right	**–0.40 (0.84)**	–0.36, 0.76	**–0.50 (0.97)**	–0.48, 0.48
Ankle	Trend normalcy	Left	0.980 (0.024)	0.953, 1	0.978 (0.021)	0.943, 1
		Right	**0.952 (0.047)**	0.979, 1	**0.946 (0.081)**	0.974, 1
	Range amplitude (ODT/OG)	Left	**0.82 (0.11)**	0.89, 1.13	**0.78 (0.14)**	0.89, 1.14
		Right	**0.85 (0.08)**	0.89, 1.12	**0.78 (0.14)**	0.89, 1.14
	Range offset (degrees)	Left	0.84 (3.28)	–1.39, 1.39	1.04 (3.76)	–1.64, 1.64
		Right	**4.49 (5.89)**	–2.18, 2.18	**3.22 (2.53)**	–2.19, 2.19
	Phase offset (% gait cycle)	Left	0.40 (1.58)	–1.08, 0.88	0.90 (1.20)	–1.26, 1.26
		Right	0.30 (2.11)	–0.63, 0.43	0.40 (1.90)	–0.73, 0.53

Note: Bolded items are outside of the 95% confidence interval for overground walking.
[a]CI = Confidence Interval.

3.3 Metabolic Cost

Normalized steady-state oxygen consumption values during walking overground and on the ODT are presented in figure 9. At both speeds, the metabolic cost of walking on the ODT was more than 20% greater than walking at the same speed overground. Additionally, oxygen consumption during walking on the ODT at 1.12 $m \cdot s^{-1}$ appears to be roughly equivalent to walking 0.2 $m \cdot s^{-1}$ (0.5 mph) faster overground.

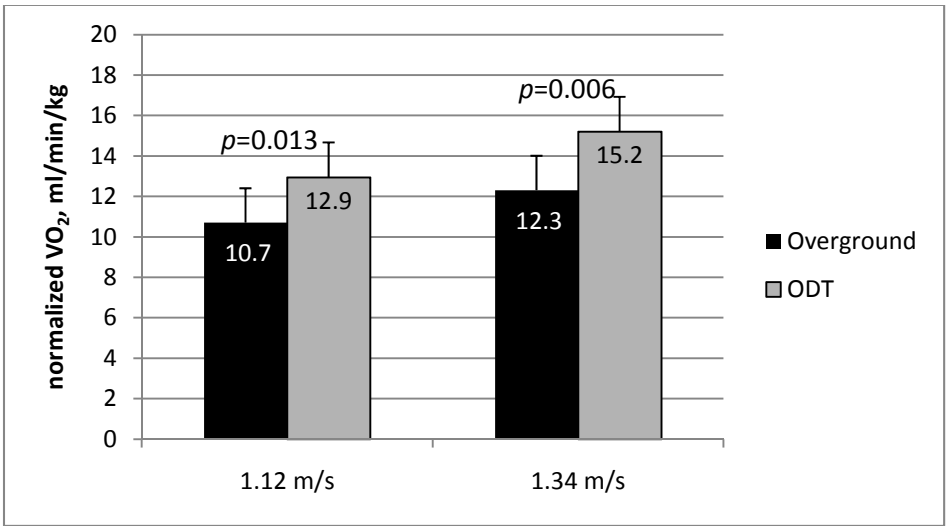

Figure 9. Metabolic cost during walking overground and on the ODT.

3.4 Ratings of Perceived Exertion

RPE values were significantly higher for walking on the ODT Upgrade at both 1.12 m•s^{-1} (p = 0.003) and 1.34 m•s^{-1} (p = 0.000). At the slower speed, both terrain conditions received ratings roughly equal to "very light" (overground = 8.5 ± 1.4 and ODT = 9.3 ± 1.4). The gap in perceived exertion levels between the two conditions widened at the faster speed, with the RPE for walking overground remaining near "very light" (8.6 ± 1.2) and that of the ODT Upgrade approaching a rating of "light" (10.2 ± 1.9).

3.5 Motion Sickness Questionnaire Response

Four of the participants reported slightly elevated symptoms after completing their trials. All four reported slight feelings of fatigue, two reported slight sweating, and one reported a slight headache. The fatigue and sweating may have been caused by the physical activity involved in the trials. However, as per the protocol, all four participants rested quietly for 15 min, after which they reported that the symptoms had subsided, and they were released from the study. Three other participants had symptoms that they reported as slight prior to the trials, which were decreased to none after the trials. Three participants reported no symptoms before or after.

4. Discussion

Incorporating the effects of realistic physical workload from traversing terrain (spatial relationships, fatigue, psychomotor control, etc.) into dismounted Soldier simulators and enhancing their psychosomatic immersion into the environment may increase the efficacy of the training effects and research results. The integration of the ODT Upgrade into a dynamic and visually immersive environment may provide for realistic, high-fidelity dismounted warrior simulations that will enable repeatable, laboratory-controlled mission rehearsal and investigations of critical Soldier issues. Additionally, this permits multisensory immersion of Soldiers into an environment that may vary from benign to hostile without exposing them to the hazards and variability of outdoor experimentation. However, the effectiveness of such simulations is dependent on the system's ability to impose biomechanical and physiological effects on the user that are similar to those experienced in the real world. The purpose of this investigation was to determine the extent to which the ODT Upgrade incorporated into the IES is capable of doing so. These findings indicate that while the ODT Upgrade permits the user to walk through a virtual environment in a relatively natural way, physiological demand is significantly increased.

In the present study, the gait mechanics associated with walking on the ODT Upgrade are, in general, comparable to those of overground walking. Cadence was found to be increased on the ODT, although only significantly so at the faster walking speed. While not statistically significant, there was also a tendency for stance time to be shorter during the ODT condition at both speeds. These findings are consistent with those of previous studies involving conventional treadmills. Similar to the respective findings of Lee and Hidler (2008) and Pearce et al. (1983), swing time and stride length were also observed to be shorter during walking on the ODT Upgrade. With the exception of an overall trend of increased flexion, there was little apparent difference in the hip and knee joint angle patterns between walking on the ODT Upgrade and overground (table 3). However, at the ankle, total range of motion was decreased bilaterally by ~20% during the ODT Upgrade conditions. Additionally, the right ankle achieved about 10° less peak plantarflexion immediately following toe-off. The increase in peak flexion and decrease in peak extension values at the hip and knee are consistent with the findings of other researchers, but neither the significant reduction in ankle ROM or peak plantarflexion angle have been previously reported for walking on conventional treadmills.

It has been suggested that the observed differences in gait mechanics of walking overground and on a conventional treadmill might be related to an attempt to keep up with the speed of the treadmill belt and avoid falling off the back of the deck (Alton et al., 1998; Murray et al., 1985) or due to an altered sense of balance and stability resulting from differences in optic flow (Lee and Hidler, 2008). Considering that the belt speed of the ODT Upgrade is dependent on the

user's own movement and that the control system is always working to move the user away from the edges and return the user to the center of the active surface, it is unlikely that a sense of urgency or fear of falling off the edge of the ODT Upgrade were responsible for the observed increase in cadence and decrease in stride length. Incorporation of the CAVE system with the ODT Upgrade allowed participants to be fully immersed in the virtual environment, thus minimizing any differences in optic flow between the two terrain conditions. Therefore, it also seems unlikely that optic flow differences contributed to the observed disparities in gait mechanics in this study. It is probable, however, that the increased cadence, decreased swing time, decreased stride length, and overall increased joint flexion on the ODT Upgrade are related to an attempt by the central nervous system to increase stability. Reducing the duration of the swing phase could result in an increased period of double-support that would, in turn, mean less time spent on a potentially unstable single limb (Marigold and Patla, 2002; Murray et al., 1985). In theory, adopting a more flexed posture should also lower the participant's center of gravity toward his or her base of support, effectively increasing stability. This is similar to what people tend to do when knowingly traversing slippery terrain (Marigold and Patla).

Despite minimal differences in temporal-spatial values and kinematics for the two terrain conditions, there is a substantially higher rate (>20%) of oxygen consumption associated with walking on the ODT Upgrade. This is higher than the 17.8% increase measured on the first generation ODT; however, that difference is likely due to the slower walking speeds (0.67 and 1.12 $m \bullet s^{-1}$) used in the previous evaluation. In the present study, the difference in oxygen consumption between the two terrain conditions increased ~3%, with an increase in walking speed from 1.12 to 1.34 $m \bullet s^{-1}$.

Although the differences in cadence between the two terrain conditions were small, they may still be worth noting considering that for a given walking speed, cadence is generally consistent within an individual (Murray et al., 1985). In a study by Umberger and Martin (2007), a 10% increase in stride rate at a fixed walking speed resulted in a nearly equal increase in energy expenditure. Therefore, it seems plausible that the 5% to 7% increase in cadence during walking on the ODT Upgrade may, in part, contribute to the substantially greater metabolic cost. Some potential sources of the remaining increase in physiological demand are differences in mechanical power, muscle activity, and arm swing.

Increased cadence at a fixed walking speed has been found to increase the mechanical work performed by the lower extremities (Cavagna and Franzetti, 1986; Umberger and Martin, 2007). It is also probable that the reduction in overall ankle range of motion and peak plantarflexion at push-off during the ODT Upgrade trials has implications on power generation at the ankle that would need to be compensated for at the hip and knee. Fixation of the ankle during walking at a set speed has been shown to increase metabolic cost by up to 15% (Vanderpool et al., 2008). Therefore, evaluation of the total and segmental work performed during walking on the ODT

Upgrade as compared to overground would likely provide more insight into how those differences in gait mechanics affect the energetics associated with each terrain condition. In this investigation, participants typically maintained a more flexed leg position throughout the gait cycle, theoretically requiring greater activation of the flexors at each joint. If the differences in gait mechanics between the two conditions are, in fact, reflective of an attempt by the central nervous system to improve balance and stability, then an increase in coactivation of antagonist muscles also seems likely. Both of these scenarios would consequently increase metabolic cost.

Arm swing during walking is believed to help regulate whole-body angular momentum by counteracting pelvic rotation (Ballesteros et al., 1965; Elftman, 1939; Herr and Popovic, 2008). It has been suggested that minimizing moments about the center of mass through controlled arm movements results in a smoother and more efficient gait (Eke-Okoro et al., 1997; Herr and Popovic). Additionally, Umberger (2008) reported that restriction of arm swing during walking increases gross energy expenditure by up to 5%. Although not quantified in this study, it was observed that several of the participants tended to hold their arms rigidly by their sides during the ODT Upgrade conditions rather than allowing them to swing naturally as they did overground. It seems likely that a portion of the increased metabolic demand during walking on the ODT Upgrade may be associated with a reduction in arm swing. There also appears to be a reciprocal relationship between arm swing and stride length (Eke-Okoro et al.), which could explain the reduction in stride length observed on the ODT Upgrade.

Perceived exertion levels for walking on the ODT Upgrade were higher than those for walking at the same speed overground. This result is not really surprising given the substantial increase in physiological demand associated with walking on the ODT Upgrade. Some participants reported that they felt they were walking faster during the ODT trials than overground, even though in actuality, the speeds were identical. Additionally, several participants commented that it was more difficult to stay on course when following the avatar in the virtual environment, especially at the faster speed. This could be partly due to the lack of visual information from the virtual environment on the ODT Upgrade surface. There is no projected image on the walking surface; therefore, the participants cannot see where their footsteps are occurring in the environment. The ground level of the virtual environment is only visible on the screens 3–4 ft out from the user's position. It could also be caused in part by the monoscopic displays, which provide no cues for depth perception. These factors may have additionally contributed to their increased RPE scores for the ODT Upgrade condition.

5. Conclusions

In conclusion, the ODT Upgrade permits the user to walk through a virtual environment in a natural way but with a significant increase in metabolic cost and perception of physical exertion. These differences must be taken into account when comparing the results of training or research studies using the ODT Upgrade to those of real-world activities. Future studies should seek to identify and develop a better understanding of the underlying causes for increased physiological demand associated with walking on the ODT Upgrade. This could aid in devising improvements to the control system or determining more optimal design characteristics for future mobility platforms to more closely match real-world physiological demands. The possibility of training individuals to walk on the ODT Upgrade in a more energetically efficient manner should also be explored.

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Appendix A. Motion Sickness Questionnaire

This appendix appears in its original form without editorial change.

Participant ID_____Date_____Condition_____

Estimating Motion Sickness Questionnaire

Please rate the following measure of motion sickness for the trial performed (or right now) by circling the word that best describes your feelings:

General Discomfort	None	Slight	Moderate	Severe
Fatigue	None	Slight	Moderate	Severe
Headache	None	Slight	Moderate	Severe
Eyestrain	None	Slight	Moderate	Severe
Difficulty Focusing	None	Slight	Moderate	Severe
Increased Salivation	None	Slight	Moderate	Severe
Sweating	None	Slight	Moderate	Severe
Nausea	None	Slight	Moderate	Severe
Difficulty Concentrating	None	Slight	Moderate	Severe
Fullness of Head	None	Slight	Moderate	Severe
Blurred Vision	None	Slight	Moderate	Severe
Dizzy (eyes open)	None	Slight	Moderate	Severe
Dizzy (eyes closed)	None	Slight	Moderate	Severe
Vertigo*	None	Slight	Moderate	Severe
Stomach Awareness**	None	Slight	Moderate	Severe
Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as a loss of orientation with respect to vertical upright.
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Appendix B. Borg Scale

This appendix appears in its original form without editorial change.

How to Use the Perceived Exertion Scale

While doing physical activity, we want you to rate your perception of exertion. This feeling should reflect how heavy and strenuous the exercise feels to you, combining all sensations and feelings of physical stress, effort, and fatigue. Do not concern yourself with any one factor such as leg pain or shortness of breath, but try to focus on your total feeling of exertion.

Look at the rating scale below while you are engaging in an activity; it ranges from 6 to 20, where 6 means "no exertion at all" and 20 means "maximal exertion." Choose the number from below that best describes your level of exertion. This will give you a good idea of the intensity level of your activity, and you can use this information to speed up or slow down your movements to reach your desired range.

Try to appraise your feeling of exertion as honestly as possible, without thinking about what the actual physical load is. Your own feeling of effort and exertion is important, not how it compares to other people's. Look at the scales and the expressions and then give a number.

6 No exertion at all
7 Extremely light

8

9 Very light - (easy walking slowly at a comfortable pace)

10

11 Light

12

13 Somewhat hard (It is quite an effort; you feel tired but can continue)

14

15 Hard (heavy)

16

17 Very hard (very strenuous, and you are very fatigued)

18

19 Extremely hard (You can not continue for long at this pace)

20 Maximal exertion

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